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WP-2631-7

# THIRD INTERIM DEVELOPMENT REPORT

## FOR

# MINIATURE THIN-FILM INDUCTORS

This report covers the period
1 December 1961 to 1 March 1962

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**MOTOROLA INC**
**SOLID STATE ELECTRONICS DEPARTMENT**
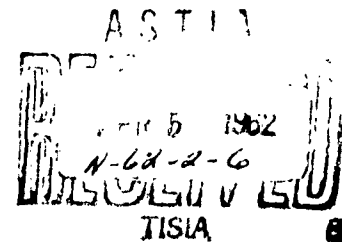**SOLID STATE SYSTEMS DIVISION**
**PHOENIX, ARIZONA**

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# ABSTRACT

The report for this period is concerned with two phases of this program. The first is the work on the fabrication of thin-film inductors on bulk ferrite substrates and the second, the deposition of thin ferrite films with a practical permeability and Q value as measured at 1 mc. The problems encountered with fabricating coils of increased inductance on commercial ferrite are reviewed and methods for overcoming these are discussed.

A number of techniques for the deposition of thin films of ferrite material are presented with particular emphasis on a method for the pyrolitic hydrolysis of metal inorganic salts to form films of the suitable oxides on selected substrates. Means for compositional, structural and magnetic analysis of the ferrite films is also included. Conclusions drawn from the program are reviewed and plans for future work are presented.

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## 1. PURPOSE

The purpose of this program is to develop a method for fabricating miniature inductors employing thin-film spiral conductors on ferrite substrates with thin ferrite films. The inductance range to be attained is from 38 microhenries to 1 millihenry with a Q value in excess of 100 at a frequency of 1 mc per second. A study of methods for lead attachment is to be made along with a measure of the voltage and current handling capability of the inductors. Six samples each of high, low and medium range inductor values are to be delivered.

## 2. GENERAL FACTUAL DATA

### 2.1 IDENTIFICATION OF PERSONNEL

The following personnel have contributed to the program during this report period:

| Name | Title | Man-Hours |
|------|-------|-----------|
| Francis R. Gleason | Physicist | 317.5 |
| L. Richard Watson | Chemist | 256 |
| Clinton Jefferson | Chemist | 72 |
| Walter Brendecke | Engineer | 25 |
| William Shea | Technician | 365 |
| Douglas Martin | Technician | 230.5 |
| Del Schonthaler | Technician | 16 |

### 2.2 MEASUREMENT PROCEDURES

The Boonton RX Meter, Model 250A, has continued to be the means for measurement of inductance values. The Boonton Q Meter, Model 260, has been used for Q values as described in the Second Interim Report for this program. Measurements of the properties of ferrite thin films will be discussed in detail in Section 3 of this report. This includes measurement of both magnetization and permeability.

## 3. DETAIL FACTUAL DATA

### 3.1 FERRITE THIN FILMS

#### 3.1.1 Background

Investigation of the techniques for depositing thin films of varying ferrite compositions was conducted during 1961, and as of 1 February 1962, has been actively integrated into the program covered by this contract. The film properties of composition, permeability, and magnetization have been measured concurrently with the investigation of deposition techniques. Each of these topics is discussed in detail in the following paragraphs.

#### 3.1.2 Film-Deposition Techniques

Film-deposition techniques that have been employed can be listed under the following categories:

    (a) Oxidation of vacuum-deposited metal films.

(b) Pyrolysis, deposition and oxidation of organometallic salts.

(c) Formulation of oxides by sublimation and hydrolytic pyrolysis of inorganic metal salt solutions.

Each method will be discussed in detail in the following sections. The order in which they are reported is not significant.

### 3.1.2.1 Formation of Oxides from Vacuum-Deposited Metal Films

Two samples of a nickel-iron film of approximately 50/50 composition were prepared by vacuum evaporation from a melt of this composition onto heated (300 C) Vycor substrates. The first sample was oxidized by heating in air at 450 C for 30 minutes. The film was transparent with a reddish-brown hue. Thickness calculated from weight differences was 0.175 microns.

The second film was thicker, and when oxidized at 760 C for 40 minutes, appeared opaque with the characteristic black ferrite appearance. It measured 1.4 microns in thickness. Using X-ray diffraction for analysis of spinel structure was not possible in the first film because the peaks obtained were not resolvable. The second film was analyzed similarly and several peaks were obtained. Interpretation of these indicated the presence of the $NiFe_2O_4$ spinel structure plus an excess of $Fe_3O_4$. This could be accounted for by the excess of iron in the original evaporated film.

No further effort was expended on this technique for the following reasons. First, there is a relatively long period of time required for the total deposition, because it is a two-step process. Secondly, there is difficulty in controlling stoichiometry, especially if more than two component systems are to be used, as is most likely the case. Finally, the thickness obtainable from practical evaporated films would be insufficient to use in an inductor application.

### 3.1.2.2 Pyrolysis, Deposition and Oxidation of an Organometallic Salt

This technique employs the use of acetylacetonate metal complex salts as the source of the nickel and iron oxides. The nickel and iron acetylacetonates were dissolved in a solvent of 50 per cent methanol and 50 per cent ethylacetate to make a 1 per cent solution. Using a spray technique, which will be described in paragraph 3.1.2.3, the solution was sprayed onto a heated Vycor substrate held at 200 C. A continuous adherent oxide film was formed which had a thickness of 0.23 microns. Continuing the spray application resulted in the removal of the initially-deposited film which peeled from the substrate. Annealing between successive thin applications did not increase the obtainable thickness by increasing film adhesion.

For successful inductor application, ferrite films must be of a greater thickness than have been obtained by this method. To increase this thickness, a reaction chamber was designed to aid in carrying the volatilized material more completely to the substrate.

The solution charge was volatized in the first chamber of a reaction train. The vapor was carried in a nitrogen gas stream through a second heated tube to the third stage where the substrate was held at an elevated temperature in the vapor stream. Temperatures of

the three stages were adjustable as was the gas flow rate. Film properties were improved slightly through the use of this apparatus, but in all cases no consistent improvement in film thickness and adhesion was obtained as preparation parameters were changed.

No further effort was devoted to this method of film formation and it was abandoned to concentrate on the deposition by spray hydrolysis of metal-chloride solutions.
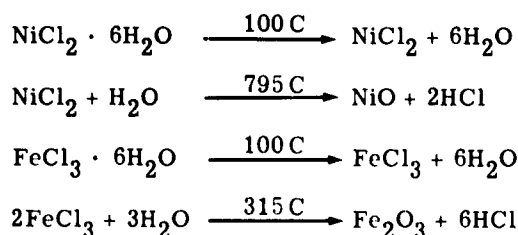
It is suspected that a difference in the energy considerations for the reactions of the different systems used can account for the lack of build-up of film thickness in the case of acetylacetonate deposition. The conditions for adhesion of the first few layers of film to the substrate appear good, but the cohesive properties of the film to itself after a certain thickness is reached prevent the film from forming to any greater degree.

### 3.1.2.3 Formation of Oxides by Sublimation and Hydrolytic Pyrolosis of Inorganic Metal Salt Solutions

This technique is based upon the fact that nickel and iron chlorides, when in the vapor phase, hydrolyze to form the oxides of the metals with hydrochloric acid as the by-product. These oxides can be condensed onto suitable substrates and annealed at elevated temperatures to form ferrite films of a spinel structure. Because of the elevated temperatures involved, Vycor substrates have been used exclusively in this study.

Both ferric and nickel chlorides are hygroscopic salts. They are normally available as the hydrates, $FeCl_3 \cdot 6H_2O$ and $NiCl_2 \cdot 6H_2O$.

Water vapor is evolved as the sublimation temperature of the chlorides is approached, and this is sufficient to hydrolyze the chloride to the oxide as the sublimation progresses. The reactions and minimum temperatures for reaction are as follows:

$$NiCl_2 \cdot 6H_2O \xrightarrow{\text{100 C}} NiCl_2 + 6H_2O$$

$$NiCl_2 + H_2O \xrightarrow{\text{795 C}} NiO + 2HCl$$

$$FeCl_3 \cdot 6H_2O \xrightarrow{\text{100 C}} FeCl_3 + 6H_2O$$

$$2FeCl_3 + 3H_2O \xrightarrow{\text{315 C}} Fe_2O_3 + 6HCl$$

Because the reactions' temperatures are different, the deposition of a nickel-ferrite film was done in two stages.

An NiO film was first sublimed onto a 0.75-inch square Vycor substrate. The film was transparent, and microscopic observation showed it to be made up of an array of tiny particles of what appeared to be nickel oxide. The film was even and quite adherent, removable only by scratching with a steel scribe.

An iron-oxide film was then deposited on top of the nickel-oxide film using the previously given reaction. The amount of ferric oxide to be deposited is determined by the desired weight ratio of $Fe_2O_3$ to $NiO_2$ of 2.14 in the desired ferrite $NiFe_2O_4$. The closest to this ratio obtained by differential weighing techniques was 2.59. This sample was subsequently heated to 850 C for 1 hour to form the desired ferrite. The finished film was opaque and

magnetic. Assuming an average density of 5 gms/cc, a film thickness of 7.2 microns was calculated.

The film showed evidence of the spinel structure by X-ray diffraction, but the excess of $Fe_2O_3$ was also shown in the diffraction pattern.

Films deposited by this technique gave acceptable adhesion and continuity. The greatest single disadvantage would be the lack of control of the process to obtain the correct film stoichiometry. Control of the stoichiometry would be even more difficult when multiple-component ferrite systems were desired.

As a variation of this technique, to aid in controlling stoichiometry, solutions of various metal chlorides which contained the desired metal ratios were prepared. These included manganese, nickel, cobalt and copper chlorides with ferric chloride as the common constituent. These solutions were applied to heated Vycor substrates which caused flash-drying of the material. After a reasonably thick coating had been applied by successive depositions, the substrates were fired at 1000 C for 16 hours to improve adhesion and to assure formation of the ferrite structure.

In all cases with each of the four metal compositions, ferrimagnetic films were formed as indicated by their possession of a magnetic moment and by X-ray indication of a spinel structure. Thicknesses, as determined by weighing, varied from 3 to 7 microns and could be partially controlled by the amount of material applied to the substrate. However, in attempting to apply greater amounts of solution to give thicknesses greater than 7 microns, the film became nonadherent and powdery.

The crystal lattice constant for the nickel-ferrite film was calculated from the diffraction pattern data to be 8.34 angstroms, which is in good agreement with the accepted value of 8.35 angstroms. This fact also indicated that the correct film structure was being achieved.

Because of a lack of sufficient uniformity and thickness, this method of film formation could not be used successfully for complete ferrite film formation.

As a variation of this technique in an attempt to overcome these limitations, the desired solutions were sprayed onto the heated substrates. A number of methods were used to accomplish this.

The first method was to use a regular mist-type atomizer to spray the correct stoichiometric Ni/Fe chloride solution into a Vycor tube held at 800 to 900 C in a tube furnace. The substrate was held vertically in the tube about 6 inches from the atomizer. It was possible to form continuous adherent $NiFe_2O_4$ films with thicknesses up to 7 microns. They were determined to be ferrimagnetic by the techniques previously mentioned. Because of the corrosive action of the metal chlorides on the metal atomizer, it was necessary to design and construct a corrosion-resistant nozzle and apparatus from glass, teflon and nylon.

To aid in directing the spray stream toward the substrate, a shaped funnel was designed and constructed from dense alumina. The funneling device was placed in the heated Vycor reactor tube between the spray inlet and the vertically supported substrate. The spray is concentrated through a square opening which conforms to the shape of the substrate.

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Films ranging in thickness up to 18 microns were deposited using this technique. They were uniform in thickness and quite adherent to the substrate. Annealing at elevated temperature, i.e. 1000 C, gave ferrimagnetic ferrite properties as mentioned previously.

Microscopic examinations of the film surface showed them to be quite granular and this granularity appeared to continue into the film depth, indicating a film of high porosity. This effect is not desirable because of a rapidly decreasing permeability with porosity.

As a possible means of overcoming porosity by faster film build-up, substitution of nitrates for the chlorides in the film spray solutions was attempted. The faster build-up was achieved, but film adhesion was poor. Mixtures of 50/50 and 10/90 nitrate to chloride were also evaluated. Adhesion remained poor. The endothermic nitrate decomposition apparently causes cooling at the point of contact, impeding the adhesion to the substrate. Therefore, chlorides remain the preferred raw material for this method because of their high solubility, availability, comparative low cost and favorable exothermic decomposition.

Because the immediate applications of this program require films of high permeability and high Q value at 1 mc, the composition of the final product is of prime importance.

Ferrites in bulk form, that possess the desired properties, are of multiple composition; for example, a ferrite of the composition $Ni_{1.4}Zn_{.573}Co_{.027}Fe_2O_3$ .

Using this ratio of constituents in the starting solution, a series of films were formed by the spray technique with thicknesses ranging from 3.1 to 18 microns. None of these films gave satisfactory electromagnetic properties.

Two films were fired at 1300 C for 30 minutes and did show an observable increase in magnetic moment, but no detectable increase in permeability was noted when a copper inductor spiral was deposited on the films. A copper spiral on a bulk ferrite usually gives a 50 to 100-per cent increase in inductance.

Because of the lack of any effective permeability, it was decided to analyze the composition of the resulting films. The first film analyzed was prepared from a manganese, zinc ferric chloride solution. The composition of the desired film was to be $Mn_{.65}Zn_{.35}Fe_2O_4$ . The analysis, however, showed a much lower zinc concentration than that in the starting chloride solution, indicating that a preferential volitization of zinc component had taken place.

To further substantiate this, a series of films of varying thicknesses of the $Ni_{.4}Zn_{.573}Co_{.027}Fe_2O_4$ composition were deposited. The thicknesses deposited were 3, 7, 10 and 18 microns.

The initial processing of the films was identical to that of the manganese zinc system followed by annealing for 2 hours at 900 C. The 3- and 7-micron films were fired a second time at 1300 C for 30 minutes. These samples were analyzed by X-ray spectrographic techniques along with a bulk ferrite of the desired composition. The analytical data is presented in Table 1. To facilitate comparison, the data is normalized with respect to the iron concentration.

## TABLE 1. MOLAR CATION CONCENTRATION

|          | Ni    | Zn    | Co     | Fe   |
|----------|-------|-------|--------|------|
| Standard | 0.400 | 0.573 | 0.0270 | 2.00 |
| Film 1   | 0.271 | 0.211 | 0.0167 | 2.00 |
| Film 2   | 0.457 | 0.099 | 0.0223 | 2.00 |
| Film 3   | 0.322 | 0.279 | 0.0224 | 2.00 |
| Film 4   | 0.264 | 0.306 | 0.0201 | 2.00 |

Examination of the data shows that except for the case of the nickel in Film 2, there has been preferential volatilization of Ni, Zn and Co with respect to Fe. Since the loss probably occurs while the cation is in the chloride form, oxygen, rather than air or nitrogen was evaluated as the spray propellant. The oxidation of the cations to the less volatile oxide form will then be accelerated. A second means of controlling the stoichiometry would be by enriching the solutions in proportion to the loss through preferential volatizations.

To observe the effect of the carrier or propellant gas, three films were deposited using oxygen as the propellant and three were deposited using air. A summary of this data, along with film thickness, is given in Table 2. Note also that variations in the mole percent of the nickel, zinc and cobalt stoichiometry of starting chloride solutions were employed. Compensating concentrations were estimated from the data obtained from Table 1.

## TABLE 2. FILM DATA

| Film No. | Calculated Thickness $(\mu)$ | Preparation Temp ($^oC$) | Preparation Time (hrs) | Propellant Gas | Chloride Solution Composition Ni | Zn | Co |
|----------|---------------------|------------------|------------------|----------------|-----------------------------|------|------|
| 1 | 19.4 | 800 | 2.5 | Air | Stoichiometric | | |
| 2 | 19.9 | 800 | 2.4 | $O_2$ | Stoichiometric Mole % Added | | |
| 3 | 20.0 | 800 | 2.5 | Air | 30 | 50 | 20 |
| 4 | 21.4 | 800 | 2.5 | $O_2$ | 30 | 50 | 20 |
| 5 | 26 | 800 | 2.5 | Air | 15 | 25 | 10 |
| 6 | 10 | 800 | 1.5 | $O_2$ | 15 | 25 | 10 |

As before, the analytical data is presented as relative cation mole ratio with respect to the film. To facilitate comparison, the data is normalized with respect to the iron concentration.

Table 3 presents the results of the X-ray spectrographic analysis of the same set of films as well as a standard.

## TABLE 3. FILM ANALYSIS

Molar Cation Concentration

| Sample | Ni | Zn | Co | $\Sigma Me^{+2}$ | $Fe^{+3}$ |
|---|---|---|---|---|---|
| Standard | .400 | .573 | .0270 | 1.000 | 2.000 |
| Film 1 | .265 | .330 | .0222 | 0.617 | 2.000 |
| Film 2 | .258 | .249 | .0238 | 0.531 | 2.000 |
| Film 3 | .485 | .544 | .0308 | 1.060 | 2.000 |
| Film 4 | .425 | .387 | .0305 | 0.880 | 2.000 |
| Film 5 | .425 | .466 | .0311 | 0.921 | 2.000 |
| Film 6 | .475 | .751 | .0267 | 1.253 | 2.000 |

The data shown in the last two columns of Table 3 indicate the relationship of the total of the divalent cations with respect to iron. Only film 6 shows an appreciable excess of divalent cations. This film is half as thick as the others and was subject to 40 per cent less processing time at the elevated temperature. The films prepared using oxygen as the propellant showed increased cation loss. It is believed that the oxidation of the metal cations prior to their arrival at the substrate allows less of the material to react at and adhere to the substrate. Also, since the hydrolytic reaction is exothermic, the energy released when the reaction occurs at the substrate aids in the formation of the desired film.

Films 3 and 5 most closely approach the divalent concentration of 1.0 mole of divalent metal to 2.0 moles of trivalent iron. Still, the desired nickel and zinc ratio has not been obtained in these films.

From this data, it is concluded that the primary problem in the ferrite film development as studied to date is stoichiometry control. Control of this stoichiometry in the spray process used for these experiments is impeded by the following characteristics.

(1) Relatively long time at the high processing temperature.

(2) A wide fluctuation in temperature during spraying which includes temperature variations up to 100 C over the median temperatures.

(3) Difficulty in reproducing processing parameters.

Based on these factors then, a new deposition system as diagrammed in Figure 1 has been designed and is being constructed. The carrier gas flow can be controlled as to pressure, rate and duration of flow by the flow meter, valve and spray nozzle. The substrates are mounted on a metallic holder whose temperature is monitored and which is heated by an r-f induction heater. Heating of the entire reaction tube in a vertical oven also accomplishes this. This system, which was completed at the end of this report period, will be evaluated during the next interim.

### 3.1.2.4 Summary

The most promising method studied for the deposition of ferrite films is by the hydrolysis of a carefully controlled metal-halide spray. This is necessary because the kinetics of the
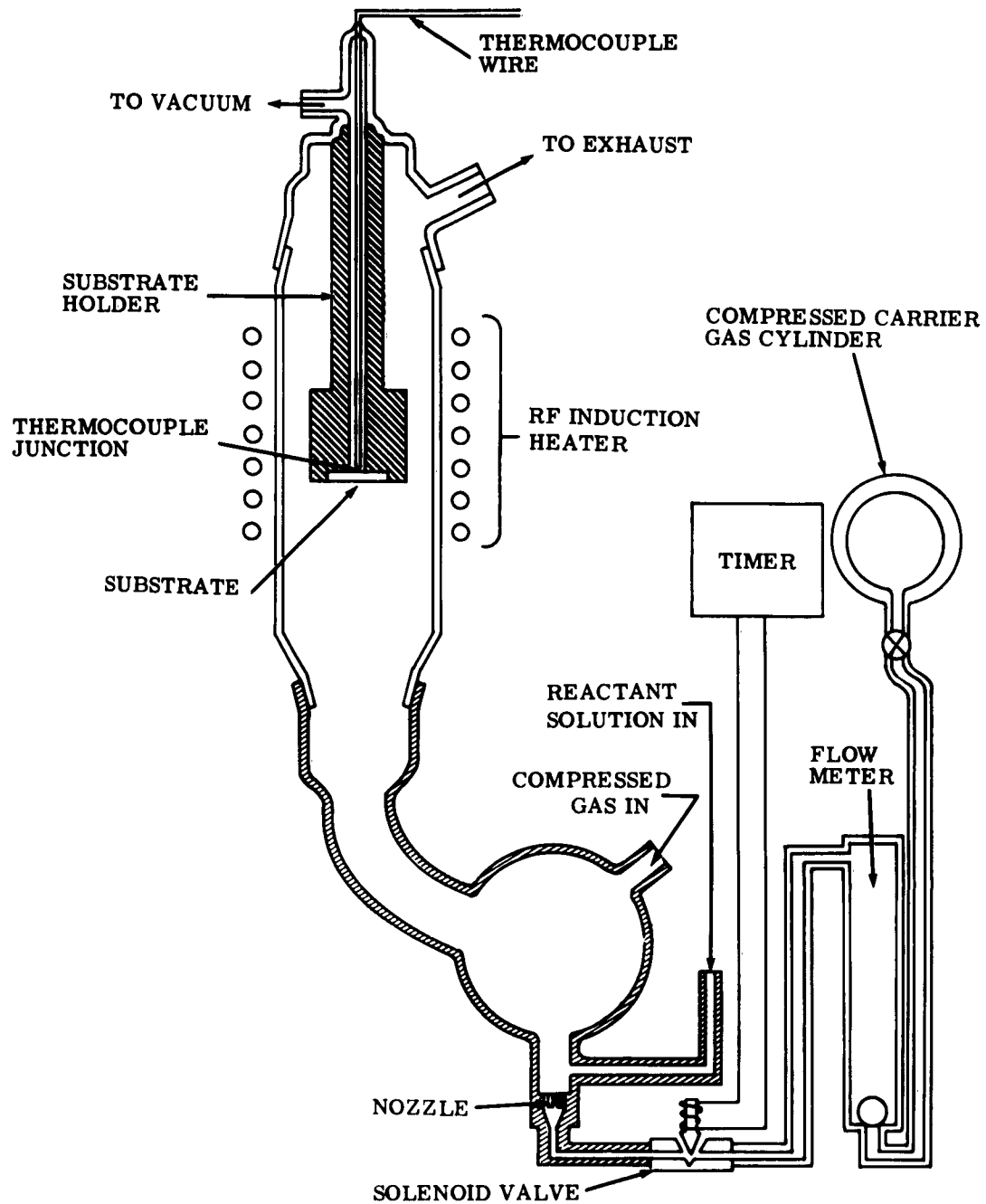
Figure 1. Ferrite Film Deposition Apparatus

hydrolytic reaction which takes place to produce the oxides for the film depends on a number of factors, including length of time that the reaction takes place, solution concentration, substrate temperature, temperature gradients along the spray path, and the nature of the propellant gas. In addition to this reaction, there is a reaction at the substrate where the formation of the spinel ferrite takes place. This reaction ultimately determines the properties of the film being produced.

### 3.1.3 Magnetic Measurements

In addition to the evaluation of the film structure by X-ray techniques, effort was devoted to measuring the film magnetic properties. The object of these techniques is (1) to determine qualitatively what, if any, magnetic moment a film might possess and, (2) to determine the initial permeability of the film. The first of these was done by the Faraday method and the second by hystersis loop measurements. Each will be discussed separately.

### 3.1.3.1 Magnetic Moment

The magnetic moment of a number of samples was evaluated using the Faraday method. This was accomplished by weighing the sample in and out of a magnetic field of gradient $\frac{dH}{dx}$. The effective gradient was determined by using a vacuum-deposited nickel film on a substrate identical to those used for the ferrite film. From this measurement of gradient and using a known value for the susceptibility of nickel, the magnetic moment for the ferrite film could be calculated.

A $4\pi M_s$ value of 3440 was determined using this method for a $NiFe_2O_4$ film whose composition had been confirmed by X-ray techniques. The accepted value for this ferrite is 3400, indicating reasonably good agreement.

The precision of this method was accomplished by actually measuring the field gradient by a probe technique. An error of $\pm 13$ per cent was determined as compared to the calculated value. This method then is at best only a qualitative tool for rapid laboratory determination of film magnetization. It proved most valuable in measuring films less than 1 micron in thickness whose spinel structure could not be determined by other means.

However, since films greater than 1 micron in thickness are to be most desired by the applications of this program, this method of magnetic evaluation was not pursued further.

### 3.1.3.2 Hysteresis Loop Measurement

From a B-H hysteresis loop obtained from a magnetic film sample, several properties may be determined. These include saturation magnetization, coercivity, anisotropy and square-loop properties. From the coercivity, an indication of initial permeability can be obtained as high coercive force materials are indicative of low permeability.

The circuit for the B-H curve tracer consists of an oscillator and amplifier for providing power to the drive coil arrangement. A voltage developed across a resistor in series with the current to the drive coils is fed to the X input of an oscilloscope. This signal is then proportional to the field being used to switch the magnetization in the film sample. The change in magnetization is detected by a suitable pickup coil wound so that the only signal

sensed is that caused by the magnetic sample. This signal is in turn fed to an integrator amplifier and to the Y terminals of the oscilloscope. Such an arrangement will produce the familiar hysteresis loop on the oscilloscope tube.

A bench model of this type of circuit was built. Although the separate elements of the circuit appeared to function satisfactorily at 1 kc, signal distortion was produced when connected as a unit.

Some of the distortion was due to 60-cycle pickup and to stray fields from the drive coils which were designed to produce a 50-oersted field. Effort will continue in order to eliminate these difficulties.

## 3.2 INDUCTORS WITH BULK FERRITE

### 3.2.1 Increased Inductance

Increasing of the inductance for a single flat air coil spiral from 1.6 to 6.4 microhenries has been the subject of continuing investigation. This was done by using 40 turns of copper conductor 1 mil in width and 1 mil space on a 0.075-inch center aperture. This configuration was initially deposited on glass without great difficulty. However, fabrication on Ceramag 9 substrates has not been accomplished. Special care was required in obtaining a flat surface for close contact with the exposure mask over its entire area. This necessitates a flat ferrite surface and an even build-up of the evaporated and electroplated copper film on the surface. The flat ferrite surface has been obtained by lapping the substrate on a Crane Lapmaster machine with No. 1000 boron carbide grinding compound. To electroplate the copper film evenly, it was necessary to mount the evaporated coated substrate in a conductive guard ring.

Several substrates were processed without obtaining a complete conducting 40-turn spiral path because of breaks in the pattern. The faults did not appear to be due to imperfections in flatness or smoothness of the copper film; therefore, a closer examination of the substrate prior to coating was preformed. This was accomplished by using increased microscope magnification and oblique illumination of the substrate surface. Detailed examination revealed a noticeable number of pits and imperfections in the ferrite owing to the general porosity of the material itself. Thus, they could not be eliminated by continual lapping and polishing of the surface. These pits were measured to be mostly between 0.5 and 0.8 mil in diameter with occasionally one as large as 1.5 mils. These larger imperfections were the source of difficulties in constructing spirals with 1-mil linewidths. A 0.8-mil pit would cause a break in a 1-mil line, whereas it resulted in only a thin spot in a 2-mil line. The 1.5-mil pits would also break the 1-mil line, and if located between two conductors, would increase the chance of a break in both of them. This same size imperfection would be almost unnoticed if it occurred between the space of 2 mils between adjacent 2-mil turns.

Because of these difficulties, some thought has been given to fabricating a spiral of 1.5-mil line and space on the 0.075-inch center aperture. Calculations showed that 27 turns would fit into the allowable diameter and this would give a calculated air-core inductance of 2.92 microhenries. Since this is only a 1.8 times increase over the 2-mil 20-turn spiral

compared to a 4.0 times increase for the 1-mil 40-turn configuration, it has been decided to continue the effort with the 1- and 2-mil linewidths for the present studies.

### 3.2.2 Air-Gap Effects

To obtain the maximum use of the initial permeability of the ferromagnetic medium used to provide the inductance coil increase, air-gap effects must be reduced to a minimum. This is evidenced by consideration of the geometry of a 20-turn spiral coil when it is fabricated on the surface of the Ceramag ferrite wafer.

This reduction of initial permeability due to the air gap is given by the following relationship:

$$\mu_{eff} \frac{\mu_o}{1 + \mu_o \frac{g}{L}}$$

where

$\mu_o$   is initial permeability

g    is gap length, and

L    is magnetic path length.

For the air-gap effect for the 20-turn spiral pattern, 1 mil in thickness sandwiched between two ferrite bodies, the following assumptions are made: the magnetic path is equal to twice the distance along the spiral turn width, i.e. 0.160 inch; the total gap is then made up of two gaps on the inside and outside of the spiral of 1 mil each for a total gap of 0.002 inch.

Substituting these values and using a permeability of 190 as reported for the Ceramag 9 ferrite, an effective permeability of 56 results. Thus, the necessity is seen for reducing the air gap between a ferrite wafer and its overlay.

A means for reducing this air gap by recessing the spiral pattern below the surface of the ferrite has previously been reported in the Second Interim Report for this program. This was the technique of directly embossing the desired spiral pattern in the pressed ferrite wafer prior to firing. One sample was prepared which had a 20-turn spiral pattern impressed in the ferrite. This recession was filled with copper by the electroless and electroplating techniques and lapped to give a flat complete conduction pattern. Measurement at 1 mc gave an inductance of 3.34 microhenries, slightly more than twice the air-core value of 1.6 microhenries. This is a slight increase over that of placing the coil directly in the surface. However, in attempting to prepare the surface of the ferrite for an overlay of ferrite material, the copper pattern was broken; hence, further measurements could not be made.

As an outgrowth of this technique, a ferrite substrate was pressed in a similar manner except that only the outline of the entire spiral was used. This permits an etched pattern to be recessed below the surface so that the overlay ferrite is in close contact at the inside and outside of the spiral with a minimum air gap resulting. Pressing of the spiral outline is more readily achieved than is the fine detail of the entire spiral. Care must be taken, however, in maintaining the same impression depth over the entire area so that the resulting

copper film deposition will have sufficient uniformity to promote uniform etching during the fabrication process. This technique has been attempted and satisfactory impressions obtained. However, since the ferrite material used did not possess optimum properties of high permeability and Q value, no spiral patterns were formed therein.

A technique for providing a recessed area in the Ceramag 9 ferrite wafers has also been investigated. For this, a grinding tool of hardened drill rod was shaped which had a 0.241-inch outer diameter and a 0.070-inch center hole. Using an 800-grit boron carbide grinding compound in a water suspension, a recession of the above dimensions was cut in the 0.25-inch square Ceramag 9 wafer. As a means of providing suitable area for the connection of the leads to the spiral pattern to be formed in this recession, a small hole was cut in the center of the 0.070-inch center area with the S.S. White air abrasive unit. Attempts will be made during the next report period to form spiral patterns in this geometry.

### 3.2.3 Mutual Inductance

To obtain inductance values approaching 1000 microhenries, more than one spiral pattern will be formed in a single package. The mutual inductance between two coils imbedded in ferrite will be utilized. Calculation of mutual inductance between two coaxial current-carrying coils is based upon Nuemann's formula:

$$M = \frac{\mu_o}{4\pi} \oint \oint \frac{\overline{dl}_1 \cdot \overline{dl}_2}{r}$$

where $\overline{dl}_1$ and $\overline{dl}_2$ are elements of length of each coil and $r$ is the scalar distance between elements.

Direct integration of this relationship proved to be difficult as values in terms of complete elliptic integrates were obtained. However, reference to Grover's "Inductance Calculations"[1] provides emperical relationships for calculating mutual inductance of like geometries with an accuracy better than that required for any practical problem. For these calculations it is assumed that two flat spirals placed coaxially can be represented by two circular coils of rectangular cross sections. The width of the coil is the thickness of the copper conductor on the substrate, and the other dimensions are similar to those for calculating the inductance of a single coil. That is, the coil depth is the number of turns times the sum of the conductor width and space, and the mean radius is equal to the center aperture radius plus half the coil depth. Since the spacing between two coils will be in the neighborhood of 50 mils and the coil dimensions are appreciable compared to this, correction factors are also included. The mutual inductance is then given by:

$$M = N_1 N_2 \left[ \frac{2M_1 + 2M_2}{4} \right]$$

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[1] Grover, F.W., "Inductance Calculation," D. VanNostrand, New York, 1946.

where

$N_1$ and $N_2$ are the number of turns in each coil and

$M_1$ and $M_2$ are mutual inductances of the coils in terms of the geometry of each.

As a comparison between the calculated and measured values, two 20-turn spirals were fabricated back-to-back on a glass substrate, 38 mils in thickness. The calculated mutual inductance for such an arrangement is 0.92 microhenries. Direct measurement gave a value of 0.95 microhenries, which is in good agreement.

When two of the same 20-turn coils as were used on the glass were fabricated on opposite sides of a Ceramag 9 wafer and covered with an overlay of the same material, no measureable coupling could be detected between them. That is, the same total inductance value was obtained when they were connected in either an aiding or cancelling configuration and this was equal to the sum of their individual inductances. This fact was borne out in two samples of this arrangement.

The reason for the lack of coupling between two coils of this geometry when separated by the ferrite is due to the presence of the air gap in the over-all medium. The assumptions that are made for calculating mutual inductance are based upon a medium of constant permeability, which is not the case with air gaps. Therefore, for the mutual inductance between the coils to be an aiding factor, the coils must be completely imbedded in the ferrite medium. This would be the case for the spiral pattern being formed in the ferrite prior to deposition of the copper conducting path.

4. CONCLUSIONS

4.1 FERRITE THIN FILMS

The problem of depositing ferrite thin films of varying compositions is a complex one. The most promising technique developed to date is the hydrolysis of metal chloride solutions sprayed onto heated substrates. The kinetics of the reaction of the chlorides to form the suitable oxides are dependent upon time, temperature, temperature gradients, concentration and pressure of the carrier gas. In addition, the formation of the oxides of the correct spinel structure on the substrate are dependent upon the condition of the substrate as the reaction products are carried to it. Also, the problem of controlling the stoichiometry of the resulting film is present because of the varying vapor pressure of the constituents.

The use of the controlled spray apparatus as shown in Figure 1 will aid in the control of these many parameters. Effort will continue on the deposition of the ferrite films using this arrangement.

A second area of investigation is the evaluation of the deposited films. The structure and composition can be determined by X-ray techniques. The direct application of inductor coils appears to be the most suitable means at present for the measurement of the magnetic properties.

## 4.2 INDUCTORS ON BULK FERRITE

Calculations of the air gap effect which lowers the initial permeability of ferrite materials show that it is necessary to reduce this effect to a minimum. The techniques for embedding the spiral patterns below the ferrite surface so that the ferrite overlay provides a close magnetic path have been described. These include grinding the ferrite obtained from outside sources and prepressing the green ferrite.

The fabrication of the 40-turn, 1-mil conductor spiral pattern will depend upon the nature of the surface of the impressions in the ferrite as described. The complete absence of imperfections possessing size magnitudes near that of the conductor width is required to form this configuration.

## 4.3 MUTUAL INDUCTANCE

The increase in inductance to be obtained by mutual inductance requires the minimization of air gap effects. It has been shown that, to obtain mutual inductance between two coils, the medium in which the coils are placed must be of a homogeneous permeability.

## 4.4 PROJECT PERFORMANCE AND SCHEDULE CHART

Figure 2 is a graphic representation of the work performed to date. Corporate-sponsored work to support Task III has been active prior to the start of Task III, and has been summarily reported herein.

## 5. PROGRAM FOR NEXT INTERVAL

## 5.1 FERRITE FILMS

Using the spray apparatus as shown in Figure 1 or with necessary modifications, attempts will be made to deposit ferrite films of 10-micron minimum thickness. The composition of the films will be related to the starting solution in terms of the preferential volitization of the constituents. The density of the films will be determined and related to the initial permeability and Q value of the material.

As films of sufficient thickness and correct composition are obtained, they will be evaluated for electromagnetic properties. Optimum methods for doing this will be determined. Finally, as films are produced which have useable magnetic properties, spiral inductor coils will be fabricated on them.

## 5.2 INDUCTORS WITH BULK FERRITE

Techniques for reducing the air gap between ferrite base and overlay will continue to be studied. This will include shaping the recession in the Ceramag 9 wafers by the grinding technique and the pressing of the recession prior to firing of the Motorola material.
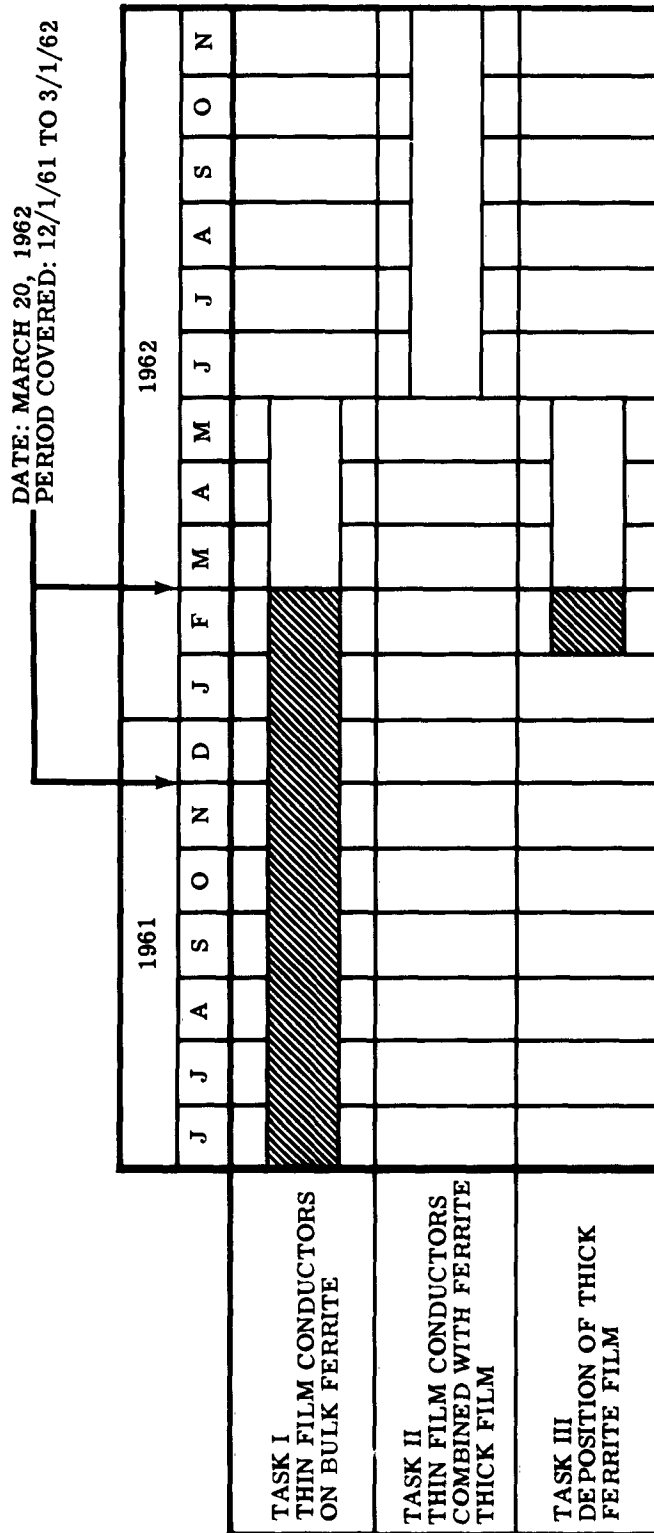
Figure 2. Project Performance and Schedule Chart

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